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Ambient Vibration Tests and Finite Element Analysis for Dynamic Properties of Brick Masonry Inverted Bell-Shaped Chedi

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Abstract

This research is aimed to study fundamental dynamic properties of an esteemed brick masonry inverted bell-shaped chedi at Phrathat Doi Suthep temple, Chiangmai, Thailand, by using full-scale ambient vibration tests associated with the finite element analysis. The study results showed that the finite element analysis indicated 3.817 Hz , 3.836 Hz and 9.294 Hz for the natural frequencies of the first modes on the x, y and torsion directions. From the ambient vibration measurements, the frequencies were 4.086 Hz, 4.025 Hz and 10.819 Hz. In comparison, the finite element gives the similar frequency values with the measured ones. The discrepancies are respectively 6.59, 4.70 and 14.09 percent. Hence, the validation of the finite element model has been made and used for vibration analysis presented in the accompanied paper (Seismic Performances of Brick Masonry Inverted Bell-Shaped Chedi)

Keywords: Natural frequency, Ambient vibration test, Finite element

1. Introduction

There are a large number of buildings in Thailand with historical significance being named the World Heritage Site. Most of the structures have been publically recognized as symbols standing as sacred reminders

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of the Buddha and the Dharma. They are also the important references for historical education in the region. It is therefore necessary to preserve these buildings for future generations.

Pagoda or Chedi, a term describing a Buddhist stupa, is one of such a kind of the historical buildings having solid inverted bell shaped geometry with no interior space in typical [1]. The geometrical dimension utilizes his self-weight enabling the brittle brick masonry material to be efficiently adopted with compressive-arch transferring mechanism under gravity loading. The buildings have been long lasted for a hundred of years with exceptional partially damaged under past potential earthquakes.

In this paper, Chedi at Phrathat Doi Suthep temple was selected as a case study. The Chedi is one of the top sacred sites to Thai people located on Suthep Mountain, Chiangmai city, Thailand. Fig. 1 shows the impressive view of the Chedi and his geometrical dimension. First, dynamic properties e.g. natural frequencies and mode shapes were investigated through ambient vibration observation. Then, finite element analysis was employed to obtain the dynamic responses in higher modes. The two results were compared to verify the finite element model and then applicable for further analyses [2].

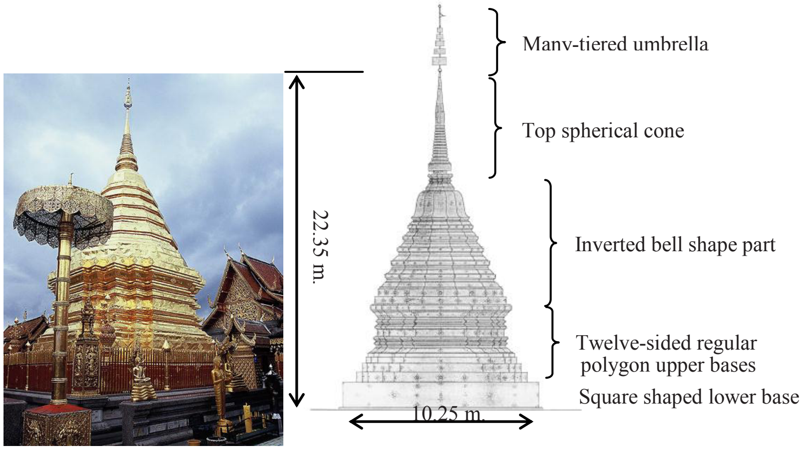

Fig. 1. Chedi Phrathat Doi Suthep

2. Ambient vibration observation and finite element model

2.1. Apparatus

The ambient vibration test for natural frequencies and mode shapes has been a subject of interest for describing the linear behavior of structures used in structural monitoring and control studies [3]-[6]. In this measurement, it was performed using velocity sensors. The apparatus was composed of (1) 3 velocity transducers with 3 directional measurements in x, y and z for each sensor (2) Cables connecting the sensors and recorder (3) Portable computer for controlling sampling rate, digital converter and duration of recording and (4) Batteries. The apparatus could detect the movements with frequency in the range of 0.1 to20 Hz and the highest velocity of 2.5 cm/s.

2.2. Measurement on ambient vibration responses

As seen in Fig. 2, for measuring the ambient vibration responses, velocity of the motions were detected using velocity transducers attached at the top part (point A). To obtain the translational vibration mode shape, another velocity transducer was placed at lower positions in z direction (vertical), e.g. B, D, E, H, I, J, K, from the top to the base. For the torsional mode shape, two opposite transducers placed at the same level in x and y directions were applied e.g. positions C, F, G and J for detecting out-phase motion.

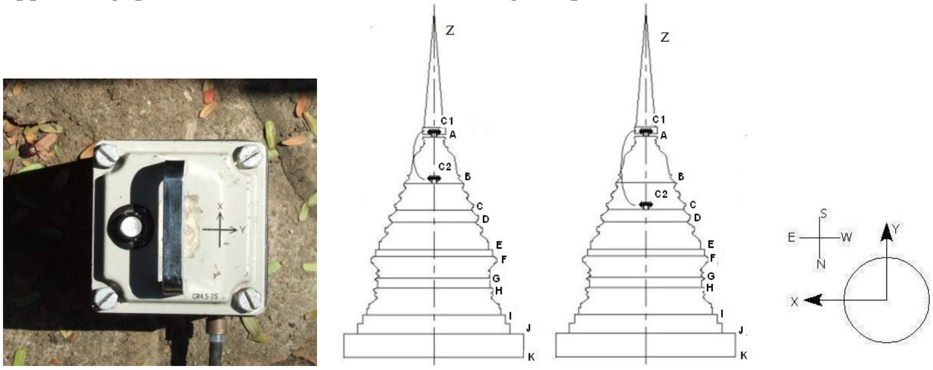

Fig. 2. (a) Velocity transducer (b) Placements of the transducers

The measured signals from the transducers were recorded for a while in time domain. Preliminary adjustments were performed for the consequence interpretation. The adjustments included relocating of wave amplitude axis for zeroing average value and extending value significant by increasing zero digits. Next, the data were transformed from the time domain to the frequency domain using the Fourier transformation technique. Then, the natural frequency could be obtained by considering the frequency at the peak of the Fourier amplitude, as seen in Fig. 3.

2.3. Finite element model

The esteemed masonry inverted bell-shaped chedi at Phrathat Doi Suthep temple has square lower base with 10.25 m. in width and upper bases below the inverted bell is twelve-sided regular polygon. Overall height is 22.35 m (excluding the height of many-tiered umbrella). Due to a heterogeneous medium with a regular laying pattern of masonry units and binding mortar, some researches adopted the microscopic discrete modelling [7], [8]. However, with the complicated geometry and large number of elements, the study adopted the other modelling approach called continuous technique. Microscopic behaviour considering interaction of composite mechanic was macroscopically assumed with a homogeneous elastic material. The commercial finite element package ANSYS program [9] was used in the three dimensional finite element model adopting 3D solid brick element coded SOLID45. The analysis was based on linear behaviour with isotropic property assumption. The many-tiered umbrella at the topmost part (see Fig.1) was modelled using three dimensional hollowed pipe element coded PIPE45 representing the vertical steel bar. Three lumped masses were assumed representing the weight of 35 kg. The model is comprised of 56,506 solid elements with 11,970 nodes. Material properties used in the analysis are tabulated in Table 1

3. Results

Table 2 shows x, y translational and torsional mode shapes obtained from the ambient vibration measurements compared with those from the finite element analyses. The comparisons show good agreement for the translation mode shapes (shown in Fig. 4) but with more difference for the very sensitive and low signal in torsional mode shape. The frequencies are quite high which can be considered as a stiff building even with the total height of 22.35 m. This results to higher earthquake force during a seismic vibration.

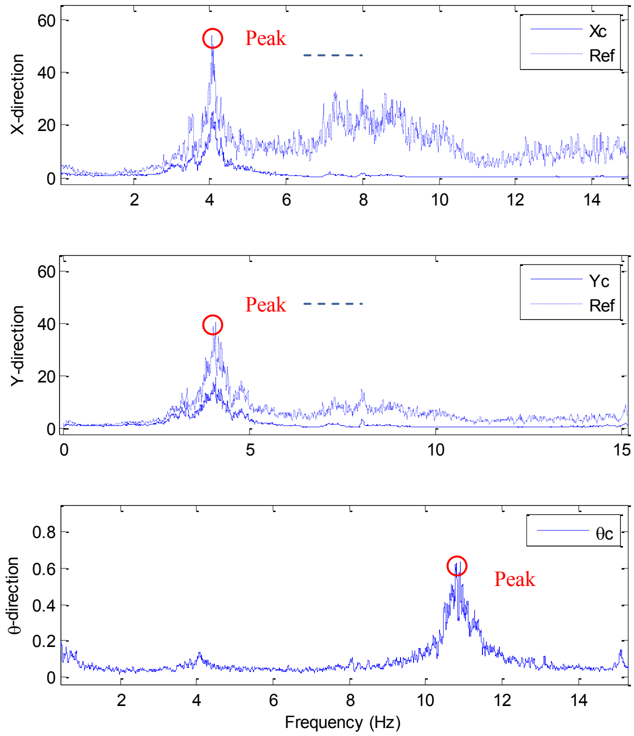

Fig. 3. Fourier amplitude with peak defined as the natural frequency (Reference point F)

Table 1. Material properties

Properties	Masonry	Steel
Young modulus (GPa)	1.0	200
Poison's ratio	0.15	0.3
Unit weight (kg/m3)	1,800	7,850
Ultimate compressive strength (MPa)	2.68	235
Ultimate tensile strength (MPa)	0.27	235

Table 2. Comparisons of natural frequencies

(Mode Shape)	Frequencies (Hz)		Error %
	Ambient vibration	Analysis	
1. x-direction (Mode1)	4.086	3.817	6.59
2. y-direction (Mode2)	4.025	3.836	4.70
3. torsion	10.819	9.294	14.09

4. Conclusion

This research is aimed to study fundamental dynamic properties of an esteemed brick masonry inverted bell-shaped by using ambient vibration field tests associated with the finite element analysis. Both results showed the fundamental frequency is in the range of stiff building characteristic (about 4.0 Hz), but with the high movement in the top part. Although, the height of the building is about 22.35 m., the frequency value is equivalent to those of low-rise (2 or 3-storey) reinforced concrete buildings. It is hence predicted that a high seismic force can be generated to the building under an earthquake event. In addition, the similar results have verified the accuracy of the finite element model and further seismic analyses have been done and presented in the accompanied paper.

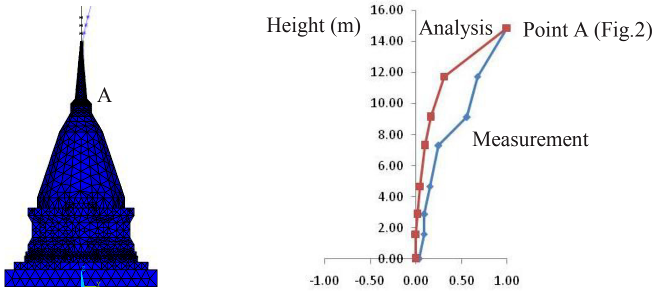

Fig. 4. (a) Translational mode shape (b) Comparison

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